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Edwards, Maurice Millett

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THE STORAGE TUBE AS AN ELECTRO-VISUAL TRANSDUCER

MAURICE MILLETT EDWARDS, JR.

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TRANSDUCER

MAURICE MILLETT EDWARDS, JR.

THE STORAGE TUBE AS AN
ELECTRO-VISUAL TRANSDUCER

by

Maurice Millett Edwards, Jr.

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
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PREFACE

The employment of the human mind as the terminus of an information system may be, at times, most advantageous for reasons of simplicity, versatility, or economy of weight and space. A radar or television system so terminated requires a transducer to convert information from an electro-magnetic form to the form of a physiological stimulus.

This paper discusses one such transducer, the RCA Direct Viewing Bright Display Storage Tube. The physiology of vision and the requirements it places upon a transducer are briefly discussed. Many of the various aspects that must be considered in the design of this tube are examined. In conclusion, some opinions are set forth concerning the applicability of the tube and the degree in which it meets the requirements for an ideal transducer.

In the preparation of this paper the writer was fortunate to have had access to progress reports on the RCA tube while engaged during the early months of 1955 as a student engineer from the Naval Postgraduate School in the Storage Tube Section of the Electron Tube Laboratory, Hughes Aircraft Co. The writer wishes to express his appreciation to Dr. A. V. Haeff and Mr. H. Millard Smith of Hughes for their hospitality and to the project engineers Dr. S. T. Smith, Dr. G. F. Smith, and Mr. N. Koda for enlightening discussions on storage tube design.

The author is particularly indebted to Professor P. E. Cooper of the U. S. Naval Postgraduate School for his encouragement and guidance in the preparation of this paper.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

The game of war demands decisions and subsequent action based upon information available. This information takes many forms, the greater part being stored information. In war it would include knowledge of our objectives, capabilities, plans, and actions, and also a certain amount of the enemy's objectives, capabilities, plans and actions. This is the information essential for strategy. When the forces enter the field, another type becomes available - tactical information characterized by much higher information rates. It is primarily geographical in nature, involving such things as the disposition of our own and the enemy's forces as well as the rates with which and the directions in which these dispositions and their component parts are moving. The decisions prompted by the receipt of tactical information may involve the choice and methods of attack, defense, deployment, consolidation, advance, withdrawal, and a host of other possibilities involving the maneuver of vessels and the control of aircraft and missiles.

Some attention has been given to the use of computers to make certain of these decisions and to initiate the required action. A homing torpedo or an automatic system which searches for and interrogates targets as well as launches and controls missiles might be conceivable examples of systems using such devices. These computers generally handle a very specialized problem by performing functions on both information stored in the system and new information made

available to it. In operation, the computer selects, from a store of prefabricated decisions, a decision that fits the information or the results of operations performed on the information. Having selected the decision, the computer initiates the action and controls the action in a predetermined manner, using the information that continues to be supplied to it. Such computers are useful where a fast continuous solution must be supplied for a stereotyped problem, such as the anti-aircraft problem, where the stored information required is fairly small. Such computers are fast, accurate, and consistent.

The limitations of computers in such systems are complexity, susceptibility to deception, lack of flexibility, small storage capacity, and greatest of all, inability to reason independently.

The advantages of using the human mind to make decisions and institute action should be considered. The brain, in its housing the body, is fairly light, compact, and mobile compared with a computer duplicating the functions of the brain. It has a tremendous storage capacity of previously acquired knowledge; it is versatile, and best of all, it is able to make independent decisions. The disadvantages of the human mind are its inability to store and act upon information delivered at high rates, its susceptibility to error when required to reach quick solutions, its quickness to fatigue, and its need for a special environment.

If it may be concluded that under certain conditions it is desirable that the human mind be used as the terminal equipment of a communication system, it must be determined how the information is

to be converted from the form in which it has been received to a stimulus that will be accepted by the brain. This may be achieved by utilizing one or more of the many senses of the human body, of which smell, taste, pressure, vision, and hearing are the five most often exercized in normal living.

The sense of smell can distinguish a great many odors which unfortunately do not share some common measurable property. Of the five, the sense of smell is least subject to fatigue. The sense of taste is limited to the recognition of salt, sweet, and sour. The senses of taste and smell do not recover quickly from having been saturated. The sense of touch, or pressure, is responsive to amplitude, frequency and location, although the ability to resolve differences in location is not great, even in the blind. The sense of hearing is responsive to amplitude, frequency, and location, although the ability to resolve differences in location is not very precise. Of the five senses, vision is the most highly developed and is responsive to amplitude, frequency, location and time. Of all the senses that resolve differences in location vision is by far the most proficient. The use of visual stimuli to represent geographical information is most desireable.

Two tactical information systems requiring transducers are radar and television. The ease with which the nearly inertialess cathode ray beam can be deflected made the television camera a reality. This property of the cathode ray beam is similarly useful in a transducer where the deflection of the beam normal to its axis may represent two variables and the beam current variations may represent

a third. In radar and television displays the location of an incremental area on the indicator may be chosen to represent two of the three dimensions of the geographical location of an object while the current to that area may represent the brightness of the object for television or the electromagnetic reflective properties of the object for radar.

If the variations of approximately 20 db expected in the third parameter were to be represented by variations in luminance in the plane normal to the cathode ray beam the picture so formed might constitute a faithful conversion of the information from its electrical form. Although not to be considered here variation in the wavelength of the light might represent a fourth variable.

The luminance range and the color chosen for the transducer should be those at which the eye demonstrates its best performance. Light, the wavelength of which varies between 3800-7800 A° and the luminance of which varies between 10^{-3} and 10^{-6} foot lamberts, is capable of producing a visual sensation [20]. The performance of the eye is not constant over the range of luminance or wavelength. In order to effect the best match of the transducer to the eye, the characteristics of vision should be set forth.

The eye "sees" by discriminating between areas of dissimilar brightness or color. The percentage difference in luminance required to discern a change of brightness between two adjacent monochromatic areas of nearly equal luminance is defined as "contrast", $\frac{\Delta B}{B}$, and is a function of luminance [6].

$$\text{"Contrast"} = \frac{\Delta B}{B} = c\left[1 + \frac{1}{(KB)^{\frac{1}{2}}}\right]^2$$

where B is the luminance, c is a constant, and K is a constant depending on the characteristics of the boundary between the dissimilar areas [10] . Generally speaking, for luminances greater than ten foot lamberts, "contrast" is a minimum equal to the constant c.

As luminance decreases the eye becomes relatively more sensitive to the blue end of the spectrum and decreasingly sensitive to the red end. This transition occurs at a luminance level of approximately one foot lambert. For luminance levels greater than one foot lambert the eye is equally sensitive to white, blue, red or green light.

Fechner's law which states that the sensation of light as produced by the eye varies logarithmically with the intensity of the stimulus is valid only when "contrast" is constant. A corollary could state that if the luminance of each elemental area of a picture is decreased proportionately, no deterioration of the image observed by the eye results.

Even at high levels of luminance "contrast" is constant only over small ranges of luminance near the luminance level of adaptation. "Contrast" increases with the difference between the luminance of the area being observed and the adaptation luminance for adaptation luminances greater than ten foot lamberts [1] .

The eye ordinarily adapts itself to the average field luminance when an object is being observed. As the illumination changes, the eye automatically changes its adaptation. The time required for

the major portion of adaptation to go to completion is 20 minutes for dark adaptation and three minutes for bright adaptation.

The resolving power of the eye is greater at high levels of luminance rather than low levels inasmuch as the ability to resolve detail involves the ability to discern differences in luminance levels.

The eye requires a finite time to see [2] . At any one luminance level, the product of contrast and exposure time is a constant for exposure times less that τ_c , the critical exposure time, which is an inverse function of luminance and takes values between 0.2 second and 0.08 second. For exposure times greater than the critical exposure time "contrast" is a constant for any one luminance level.

The retina of the eye may be divided into concentric zones, called the foveal, parafoveal, and peripheral regions, intercepting at the iris central angles of one, three, and 20 degrees respectively. Their respective contrast sensitivities (reciprocal "contrast") are in the ratio 15:3:1.

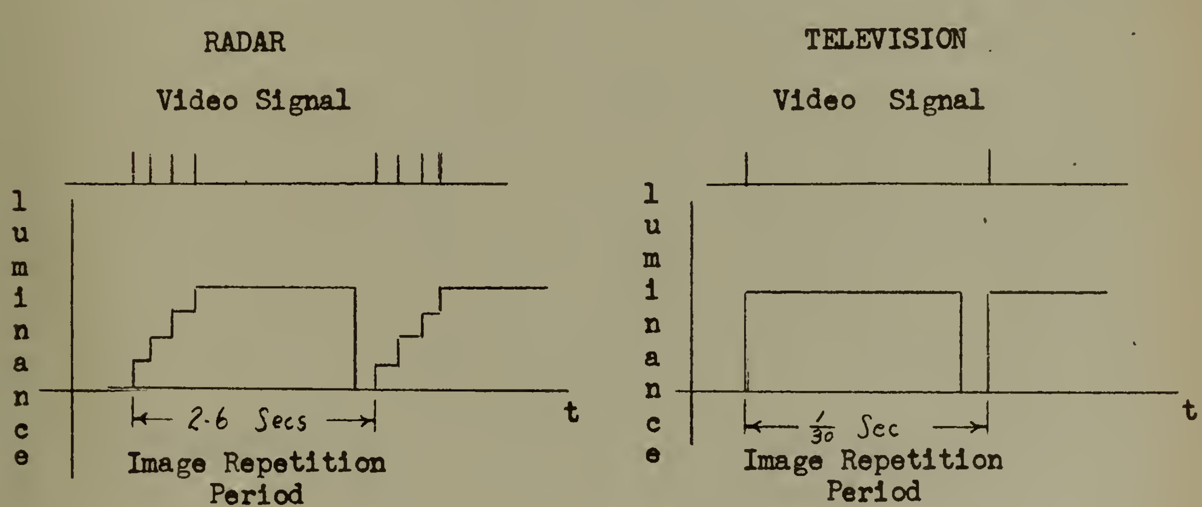
In general the amount of information the eye can extract from a picture depends upon the manner in which the eye scans the picture. Assuming the eye remains focussed at any one spot 0.2 second before moving to the next spot to be examined, the times required to scan a five inch diameter display at a viewing distance of 12 inches foveally, parafoveally, and peripherally are 4.28 minutes, 8.1 seconds, and 0.2 second respectively. The amounts of information extracted are roughly in the ratio 15:3:1, respectively.

From a consideration of the characteristics of vision alone it

is apparent at the outset that the visual display produced by the transducer should be one whose range of luminances lies above ten foot lamberts. Furthermore, the luminances of the constituent parts of the display must be maintained at their initial levels until new information is to be presented or until the eye has assimilated all the information desired from the display. From the standpoint of sensitivity the choice of color is immaterial for the levels of luminance proposed. Consideration of the properties of the radar and television signals to be transduced may lead to additional requirements.

In radar the number and amplitudes of the radar echoes received from the target per scan are indicative of the nature of the target. The transducer should provide for the integration of these echoes.

The luminance, as a function of time, of an elemental area of the viewing screen of an idealized transducer is sketched below:



Visual Output of Ideal Electro-Visual Transducer

FIGURE I

It may be observed that, generally speaking, the image repetition period is not long enough to permit the eye to obtain the maximum amount of information the picture may contain. The image repetition period may be as long as six seconds for an azimuth search radar, whereas the time required to examine the picture superficially is about eight seconds, or more thoroughly up to four minutes. In television the image repetition period (field period) is one thirtieth of a second whereas the time required to achieve even a fleeting impression is about two tenths of a second.

Neglecting the fact that a tremendous amount of the information is redundant from scan to scan it is apparent that some information will be lost if the viewing time for each elemental scanned area is less than the critical exposure time because larger values of "contrast" are thereby required to discern differences in luminance. Furthermore, if the overall luminance of the image decays during the image repetition period the amount of "contrast" required is further increased first because the lower luminance levels, in general, require more "contrast", except at luminances in excess of 20 foot lamberts, and second because the luminance of the scene differs continuously from the adaptation luminance, requiring more "contrast".

The use of partial erasure of the stored information at the end of the image repetition period depends upon the desireability of scan to scan integration or a certain amount of smearing. Complete erasure may be desired for both radar and television presentation especially when information in the display changes significantly during an image repetition period. Ideally, erasure should scan

the display in the same selective manner as does the recording cathode ray beam.

The possibility that the desired information may appear on but one scan as in the detection of weak radar signals makes the considerations stated above particularly significant especially if all or part of the old information is removed at the end of the image repetition period.

The transducer required for the systems under consideration must be capable of the following:

1. Record internally a faithful reproduction of the signal received from the communications system.
2. Retain the recorded information as long as desired.
3. Present a faithful reproduction of the information stored in a bright visual display.
4. Erase all or any part of the stored information.
5. Perform all four of the above functions simultaneously.

CHAPTER II

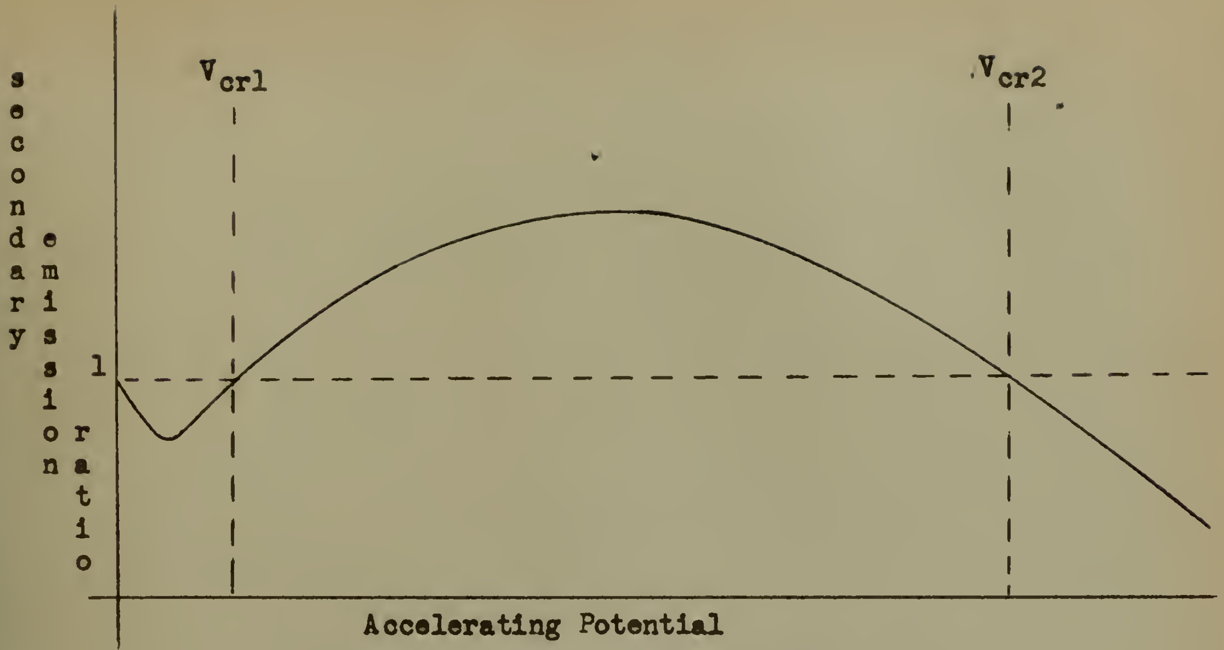
PROPOSED DIRECT VIEWING STORAGE TUBES

A number of transducers, described in the literature, have been proposed for the conversion of information from the electrical form to the visual form. They may be classified into two types, electrical-electrical and electrical-visual.

Electrical-electrical transducers are essentially frequency conversion devices. Information received in the electrical form is recorded in the device at the usual scan rate and is subsequently read-out electrically at a much higher scan rate. The electrical output is then delivered to a conventional cathode ray tube. The persistent high brightness display obtained is the result of the high duty cycle of the output scanning and the non-destructive readout. The electrical-electrical transducer offers the advantage of providing from one special device a bright display to more than one conventional indicator. Not withstanding this advantage the development of an electrical-visual transducer has been prompted by the limitations and disadvantages of the electrical-electrical transducer enumerated here:

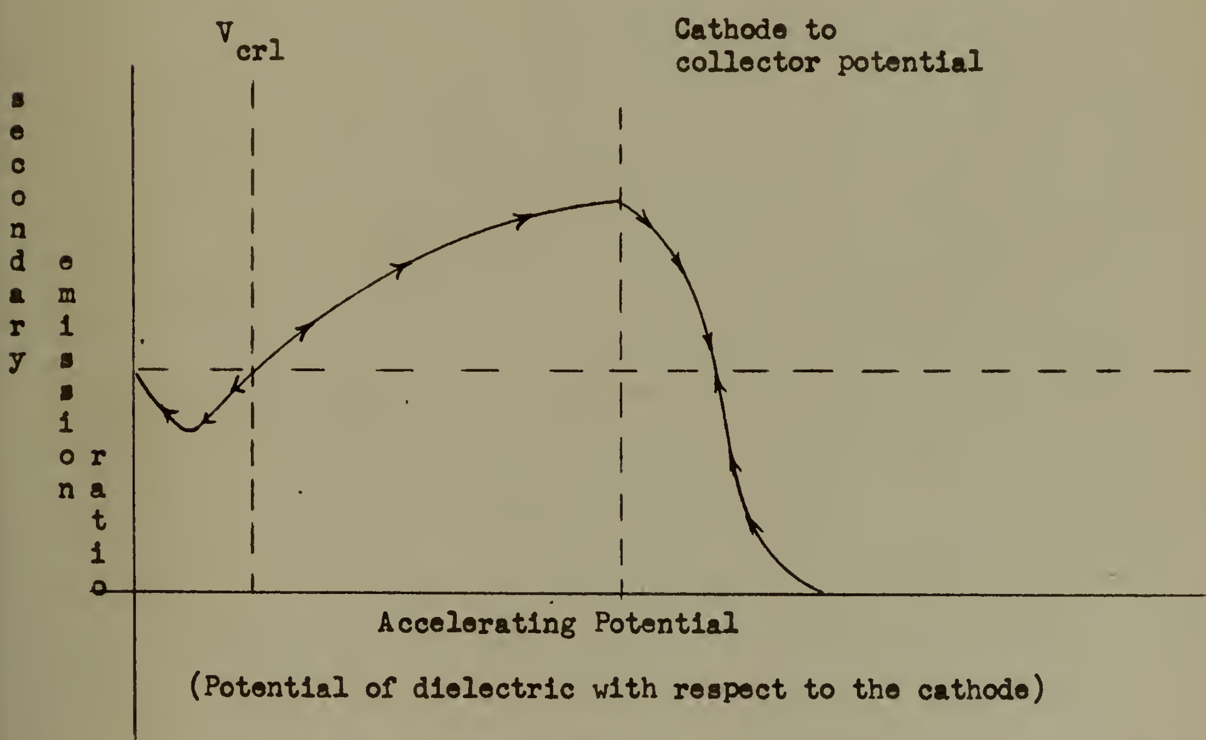
1. Extensive complex external circuitry is required.
2. The requirement for high potentials in the indicators is not relaxed.
3. It is difficult to completely separate the reading and writing signals in the output.

A number of electrical-visual transducers have been proposed. [9]



Typical Secondary Emission Curve

Figure 2



Typical Effective Secondary Emission Curve

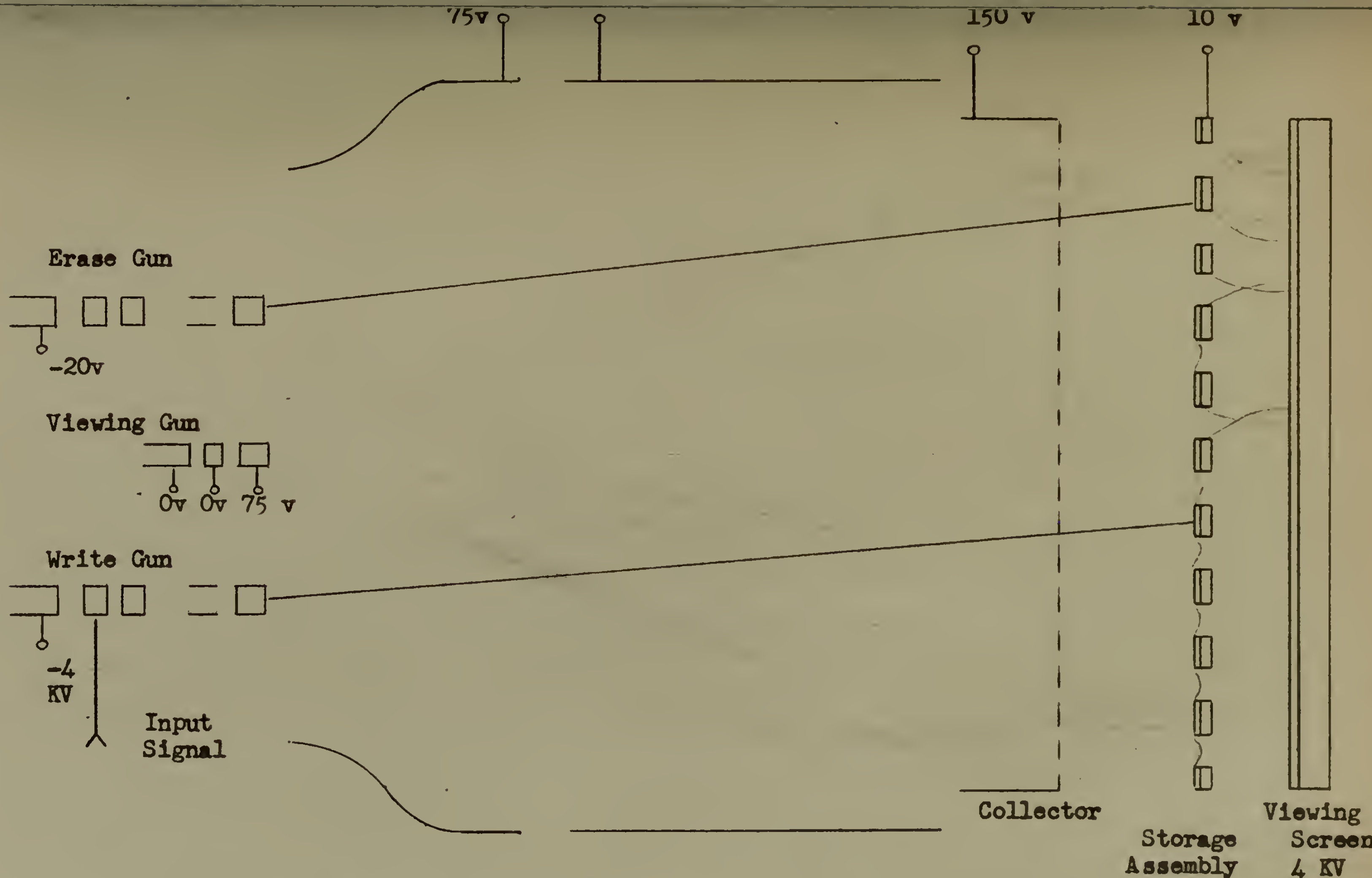
Figure 3

A fairly comprehensive survey of these devices has been made by Knoll and Kazan. Without exception those described fail in one degree or another to meet all the specifications established in the previous chapter for an ideal transducer. Tabulated below are the names of the tubes and their disqualifying features.

Hergenrother and Gardner Tube	No simultaneous reading and writing
Haeff Memory Tube	No half tones
Knoll and Randmer Tube	Poor resolution. Time sharing of write and erase functions
Donal and Langmuir Tube	Extremely short persistence
Knoll and Rudnick Tube	High potential writing with resultant slow writing speed and excessive internal noise
Schroeter Tube	Low brightness

Another transducer, the RCA Direct Viewing Storage Tube, has been developed under the guidance of Dr. H. M. Knoll of David Sarnoff Research Center. Of all the electrical-visual transducers currently proposed the RCA tube best satisfies the requirements set forth for the ideal transducer. The tube will be first described in brief and then, in succeeding chapters, in considerable more detail.

Inasmuch as the principles of insulator secondary emission are utilized in this tube they are briefly reviewed here. Figure 2 is the curve of secondary emission ratio (the ratio of collected secondary emission current to incident primary current) as a function of electron striking velocity in electron volts. The points labeled V_{cr1} and V_{cr2} are the first and second critical potentials, hereafter



Outline Schematic of Direct View Storage Tube

Figure 4

referred to as the first and second crossovers. Under continuous bombardment the dielectric surface can assume either of two equilibrium potentials, cathode potential of the electron source or a potential slightly positive with respect to the collector. For any given acceleration potential the dielectric charges in the direction shown by the arrows in Figure 3.

The storage tube (Figure 4) is essentially a CRT where the conventional viewing screen has been replaced by the storage assembly, a mesh screen coated with dielectric on the electron gun side. A close spaced mesh collector whose gradient to the storage assembly is about 1000 volts per inch is inserted on the dielectric side parallel to the storage assembly. A viewing screen whose gradient to the storage mesh is about 25 KV per inch is placed parallel to the storage surface on the storage mesh side. Prior to recording (writing) the potential of the uncharged dielectric surface is translated below ground through its capacity to the storage mesh. A focussed intensity modulated high velocity electron beam writing between crossovers scans the surface of the dielectric in a conventional manner establishing by secondary emission a charge pattern over the storage surface. The storage assembly in conjunction with the collector and viewing screen fields now constitutes a matrix of individual coplanar electron lenses one at each hole in the storage mesh. The dielectric of the storage surface is continually flooded with normally incident viewing electrons whose velocities preclude their landing on the storage surface. The passage of these low velocity electrons through the storage mesh into the strong accelera-

tion field of the viewing screen is controlled at each of the individual holes by the charge distribution residing about it. The image thus produced on the viewing screen is a replica of the charge pattern established on the storage surface by the writing gun. To enable the writing of new information erasure of the charge pattern is achieved by directing electrons with acceleration potentials slightly below the first cross-over at the storage surface. The potential of those areas struck by these electrons will shift towards cathode potential. These erasing electrons may originate from a flood gun or if selective erasure is desired from another focussed electron gun.

The description just given is simplified to the barest essentials. The next chapter will discuss each of several design aspects of the tube. The interdependence of the functions of the tube will be revealed apprising the reader of the engineering compromises necessitated to achieve any given set of operating characteristics.

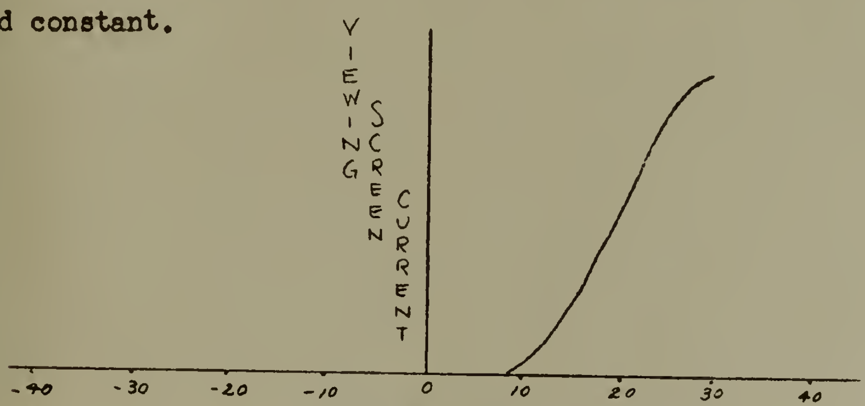
CHAPTER III

DESIGN FACTORS INVOLVED IN THE RCA TECHNIQUE

1. Control Characteristics

During the normal operation of the storage tube the potentials of the collector and the storage mesh are maintained at some constant potential with respect to the grounded cathode of the viewing gun. This condition facilitates the visualization of the tube in its viewing process as a triode where the viewing gun constitutes the cathode, the dielectric surface the grid and the viewing screen the anode.

A curve similar to the transfer characteristic of a triode called the control characteristic may be determined for the tube where the abscissa is storage surface potential and the ordinate is viewing screen brightness or viewing screen current. Figure 5 shows the typical form a static control characteristic would take where the potential of the storage mesh is adjusted to maintain a constant gradient through the dielectric, all other electrode potentials held constant.



Storage surface potential

Typical Static Control Characteristic

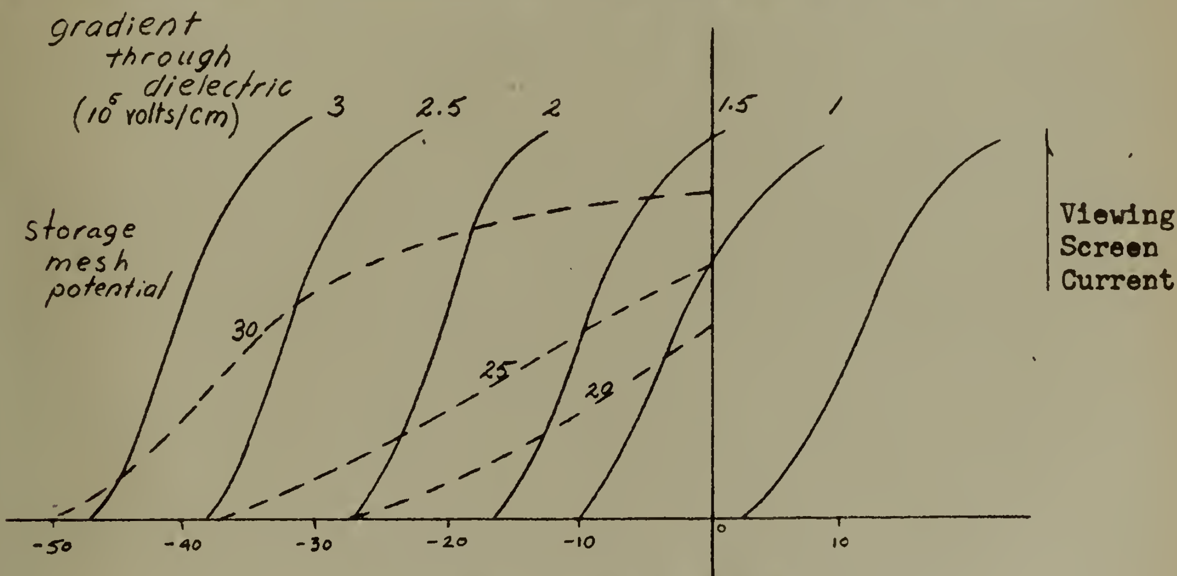
Figure 5

The lateral position of the static characteristic curve is a function of the following parameters:

1. The gradient from the storage assembly to the viewing screen.
2. The gradient from the storage assembly to the collector.
3. The gradient through the dielectric from the storage surface to the storage mesh.
4. The transparency of the storage mesh (ratio of the area of the hole to the area of the dielectric about each hole controlling the flow of electrons through it).

Increasing any of these parameters serves to translate the characteristic curve to the left.

If the storage mesh potential is held constant it is apparent that the gradient through the storage dielectric varies across the storage surface with the potential at each elemental area of the



Storage Surface Potential

Construction of Dynamic Control Characteristic

Figure 6

storage surface. The control characteristic representing the actual condition of operation would then be a dynamic control characteristic constructed as shown in Figure 6 from a set of static control characteristics for various gradients through the dielectric. A number of dynamic characteristics characterized by different shapes and cut-off values is possible. The nature of the dynamic characteristic curve desired for this tube is established by consideration of other phenomena that may occur in operation.

It must be recognized that the landing of viewing electrons on the storage surface will cause the surface to charge negatively towards the potential of the grounded viewing cathode destroying the pattern of charges deposited by the writing beam. Therefore, the useful dynamic range of storage surface potential must lie below ground potential. Because ground potential is a stable equilibrium potential for the storage surface zero voltage on the storage surface represents the condition of maximum viewing screen current or brightness.

A long control range is desireable for the following reasons:

1. A fixed amount of internal noise caused by non-uniformities of various kinds in the tube constitutes a smaller percentage of the range.
2. The useful viewing duration (persistence) is increased.
3. The percentage change in viewing screen luminance per volt change in storage surface potential is decreased yielding more easily controlled half-tone

reproduction.

A short control range permits the realization of high writing and erasing speeds. However, a long control range is usually sought relying on other techniques to increase writing and erasing speeds.

The starting point in the selection of parameters to achieve the desired dynamic control characteristic is the transparency of the storage mesh. Resolution requirements establish the pitch or number of holes per linear inch and the strength requirements of the mesh fix the transparency. The pitch of the mesh for small diameter tubes may run as high as 500 to 700, which places the control characteristic well into the positive storage surface potential region for moderate collector and viewing screen gradients. The maximum collector-dielectric gradient is controlled by field emission, collimation, and writing speed considerations and seldom exceeds 1000 volts per inch. The maximum viewing screen-storage mesh gradient, seldom exceeding 40 KV per inch is controlled by field emission and voltage breakdown limitations. The dielectric surface-storage mesh gradient is limited to 10^6 volts per inch, which for a two and one-half micron thick storage surface is a 100 volt potential difference between the storage surface and the storage mesh.

With the gradients to the collector and the viewing screen maximized within their limitations it may be seen from Figure 6 that the choice of the fixed storage mesh potential not only affects the useful range of the dynamic characteristic but also its shape and slope. The maximum brightness is also affected.

The shape desired in the dynamic characteristic is established

by the relationship desired between the sensation produced by the eye and the information extracted from the original source. In the case of television, the relationship between the luminances of the constituent parts of the displayed picture should be the same as those in the original scene.

To avoid complicating the discussion assume that the dynamic characteristic of the storage tube is linear, the response of the television camera to luminance is linear, and the change in storage surface potential, for uniform writing scan speed, is linear with writing beam current. If writing beam current were a linear function of video grid signal the displayed picture would have the requisite characteristics. However, $i_b = k\,(e_c - e_{co})^n$ where n is two or greater. This condition is remedied at the television station by taking the nth root of the camera video amplitude before modulating the carrier, using a device called the rooter [14].

The linear dynamic curve is, therefore, quite satisfactory when the tube is to be used for television purposes. Since contemporary design of the tube is pointed toward a long linear characteristic comment on the application of the tube as a radar indicator is reserved for the conclusions.

2. Choice of Dielectric

The characteristics demanded of the storage dielectric are:

1. High resistivity to prevent the leakage of charges over the surface with a resultant deterioration of the stored picture.

2. Uniform thickness so that the capacitance of the storage surface seen by the writing beam will be a constant over the entire surface. For a uniform scanning speed and fixed writing beam current this means a constant charge removed from a constant capacitance over the surface. A uniform storage surface potential obtains resulting in a uniform screen brightness. Variation in the thickness contributes internal noise.
3. Uniform secondary emission ratio to provide uniform charging and discharging rates.
4. A large value of secondary emission ratio, approximately equal to two, to provide high writing speeds and to minimize the effects of non-uniform secondary emission.

Calcium fluoride, zinc sulfide, glass, talc, and magnesium fluoride have been among those dielectrics suggested for use in storage tubes. Calcium fluoride permits good viewing duration and high writing speeds but is difficult to erase. Shortly after erasure the erased pattern will reappear. Calcium fluoride is, however, easy to apply and has good mechanical properties. A glass dielectric resulted in low writing speed. Thick sprayed talc exhibits a hysterisis type control characteristic which is intolerable. Magnesium fluoride was found to have insulation properties superior to those of calcium fluoride. In order to provide uniform dielectric thicknesses the dielectric is evaporated onto the storage mesh. To prevent crazing of the deposited magnesium fluoride surface the

storage mesh must be held at 300° C. during evaporation. Even so, the surface will craze if the deposited thickness is much in excess of two microns. To improve writing speeds magnesium fluoride has been evaporated on a sub-stratum of zinc sulfide, increasing the dielectric thickness and decreasing the capacitance presented to the writing beam, without losing the desireable properties of magnesium fluoride.

The resistivity of the storage material can be determined by observing the deterioration of the stored picture after specified intervals of time during which all tube potentials have been removed.

Optical methods can be used to measure variations in deposited film thickness which are of the order of 15 percent from center to edge. These methods provide a means of evaluating techniques designed to improve thickness uniformity.

3. Writing

To cause white on black writing on the face of the viewing screen the areas of the storage surface being written upon must charge positively from cut-off potential. Secondary emission ratios greater than one are obtained with writing beams whose acceleration potentials lie between crossovers of the secondary emission curve. The initial charging current (electron flow) leaving the storage surface, considered as one plate of a parallel plate capacitor, is $(\delta - 1) I_b$. If the change of potential in the written area is a small fraction of the difference in potential between unwritten areas and the collector the charging process may be considered linear.

Using these assumptions and a technique similar to that used by Hergenrother and Gardner the writing speed may be expressed as follows [7] :

$$v = \frac{K(11.1) \times 10^{12} \; \alpha_1 (1 - \alpha_2) \; (\delta - 1) \; I_b \, d}{k \cdot d_b \quad \triangle E} \quad \text{meters/sec}$$

α_1 = transmission of collector

α_2 = transmission of the storage mesh

I_b = writing beam current

d = dielectric thickness

k = dielectric constant

d_b = diameter of writing beam

$\triangle E$ = change of storage surface potential

δ = secondary emission ratio

K = charging factor, taken by Hergenrother as 1/2

If the following values may be assumed for a tube:

$\alpha_1 = 0.80$	$I_b = 10 \times 10^{6}$ Amp	d_b = 305 microns
$\alpha_2 = 0.40$	$\delta = 2.0$	d = 2 microns
$k = 5$	E = 5 volts	

the equation yields a writing speed of 3.5 KM/sec. An actual writing speed of 2 KM/sec has been observed under similar circumstances. The equation assumes a beam of uniform current density and square cross section rather than one of circular cross section and gaussian current distribution as is actually the case.

From the expression for v it may be observed that writing speed

may be increased, without detrement to either useful viewing duration or brightness (see sections on persistence and brightness), by increasing either the secondary emission ratio or the beam current density. Increase of the latter by decreased beam diameter also results in improved written resolution. Use of maximum secondary emission is also desired to minimize the variations in charging current caused by non-uniformities in secondary emission ratio over the storage surface.

Writing speed might be improved tremendously using the phenomenon of bombardment conductivity [15] . Electrons in the dielectric absorbing sufficient energy from the incident high energy writing beam are elevated to the conduction band where the gradient across the dielectric translates them to the storage mesh charging the dielectric positively. The ratio of this current to the exciting current is the conduction ratio. However, to preclude the loss of insulation in the dielectric due to heating, moderate writing potentials must be employed. At such potentials the film thickness required for maximum conduction ratio (about 10) is about 0.25 microns. The low erasing speed for a storage surface thickness of 2.5 microns is lowered even further by this increased capacitance of the storage assembly. Therefore, thin dielectric films are not used and the actual conduction ratio is low, less than one-half (estimated from available curves [15]).

The secondary emission ratio is also a function of the angle of beam incidence as follows: [13]

where

δ_θ = yield at incidence angle θ

δ_0 = yield at zero incidence

x_m = mean depth of liberation of secondaries

α = coefficient of absorption of secondaries

If it may be assumed that the angle of incidence departs from the normal by no more than 20°, the variation in secondary emission ratio over the surface does not exceed six per cent. The writing gun is mounted off-set from but parallel to the tube axis. Positioning voltages center the beam to the axis about which the beam is deflected to minimize the maximum angle of incidence.

4. Reading or Viewing

Viewing is the controlled flow to the viewing screen of a uniform flood of electrons parallel to the axis of tube by the lattice work of lenses in the storage assembly. This flood of electrons might be produced in any of a number of ways. A planar cathode might be employed but uniform emission would be difficult to achieve and room would not be available for the writing or selective erasure guns. A group of viewing guns symetrically dispersed about the tube axis might also be considered. Overlapping of the beams would, however, produce a non-uniform flood at the storage surface. A single defocussed flood gun mounted on the axis of the tube could produce a fairly uniform flood of electrons. This method appears to be the simplest and is the one employed.

It should be determined at this point what tolerances are

permitted in the angle of incidence of the viewing electrons on the plane of the storage surface. If all the electrons approaching the storage surface are taken to have the same speed then the axial components of the velocities may be expressed as functions of θ, where θ is the angle the path of the electron makes with the normal to the surface.

Let-

V_1	$= K\sqrt{V}$	axial velocity of electron normal to the surface
V_2	$= K\sqrt{V}\cos\theta$	axial velocity of the electron making the largest angle

Then the difference in potential required to repel these two electrons from the storage surface, delta cut-off, is simply

$$\Delta_{c.o.} = K\sqrt{V}\,(1 - \cos\theta)$$

Consequently, if the storage surface is to provide for a uniform cut-off, the electrons must be decelerated before striking the storage surface and the angle θ must be made as small as possible. The latter is achieved by proper collimation, discussed in another section.

The cathode of the writing gun is set at ground potential. This insures that viewing electrons will not strike written areas which have potentials less than ground. Areas which have either been written or have faded up to potentials higher than ground will be discharged to ground by the erasing action of the low velocity viewing electrons.

The amount of beam current is, of course, one of the parameters

contributing to the maximum brightness of the tube. The maximum desireable beam current is limited by the residual gas pressure in the envelope. The viewing beam cathode can without effectively reducing its performance partially clean up the tube by adsorbing ions. Viewing beam current may be increased to the point where the ions cause effective poisoning of the cathode.

The amount of beam current that can be delivered to the storage mesh is also controlled by other practical considerations. Maximum viewing current may be achieved by causing the viewing beam first to diverge to a large diameter, then to converge to a diameter where space charge divergence will adjust the diameter of the beam to that required. The necessity for a large diameter lens would unduly increase the diameter of the envelope with respect to the diameter of the viewing screen.

To keep the envelope diameter only slightly larger than the viewing screen diameter a compromise is used in the design of the viewing gun. The beam is initially caused to diverge only slightly, the remainder of the divergence being caused by space charge divergence. The beam is diverged to a diameter only slightly larger than the diameter of the viewing screen. The resultant beam current is somewhat less than optimum.

5. Collimation

The need for collimation has been established in the section on viewing. The wall coating of the cylindrical envelope is divided to provide two lenses, one convergent at the shoulder of the tube, and

one divergent at the viewing end.

Poor collimation is principally the result of spherical aberration. The permissible lack of collimation sets the upper limit on the amount of spherical aberration that may be tolerated. This, in turn, fixes the length and diameter of the tube. Aberration increases with decreasing focal length and with the increase of the ratio of focussed beam diameter to the lens diameter. If a fixed amount of aberration is not to be exceeded, increasing the solid angle of the viewing beam for the same focussed beam diameter requires an increase in the lens diameter. Conversely, increasing the ratio of beam diameter to lens diameter demands a longer focal length.

The quality of collimation may be determined using a tube in which the only change from conventional design is the use of a bare storage mesh. The storage mesh potential is varied about ground potential, the other tube potentials being maintained at their normal values. The range of storage mesh potential required to cut off all parts of the viewing beam is a measure of delta cut-off and the quality of collimation.

6. Brightness

The principal factors contributing to the maximum brightness are the amount of total viewing beam current, the partition of beam current by electrodes other than the viewing screen and the viewing screen potential.

The maximum viewing beam current is limited by the collimation requirements which are set by the permissible size of the envelope.

The partitioning of the current to the wall coating and the collector mesh are functions of the nature of the collimation and the transparency of the collector and storage meshes.

The viewing plate potential contributes energy to the beam which is, in turn, converted into light energy. If the light produced at the phosphor is emitted equally from both sides of its surface the energy conversion equation is

$$1 \ \frac{\text{watt}}{\text{cm}^2} = 151.5 \times 10^3 \text{ foot lamberts}$$

and if radiation is from but one side:

$$1 \ \frac{\text{watt}}{\text{cm}^2} = 303 \times 10^3 \text{ foot lamberts}$$

The apparent efficiency of the phosphor has been computed for each set of experimental data shown below which points up the benefits of an aluminized screen.

Screen Diam.	Screen Pot.	Screen Current	Observed Brightness	Calculated Brightness	Phosphor Efficiency
5 in.	8 KV	.8 MA	145 F. L.	$7.65 \cdot 10^3$FL	1.9%
4 in.Al	5 KV	.25 MA	100 F. L.	$4.83 \cdot 10^3$FL	2.07%
4 in.Al	9 KV	.25 MA	500 F. L.	$8.68 \cdot 10^3$FL	5.76%
4 in.Al	15 KV	.25 MA	1300 F. L.	$14.5 \ 10^3$FL	9.0%

It becomes apparent that aluminizing the viewing phosphor not only doubles the light output but improves the apparent efficiency of the phosphor as well.

Ball milling of the phosphor before application of the phosphor and aluminized backing reduces the probability that the aluminum will

spall under the high gradients used for maximum brightness.

7. Erasure

Two types of erasure are suggested in the half-tone mode: overall partial erasure or selective line by line erasure.

Overall partial erasure is achieved by spraying the storage surface with collimated electrons whose acceleration potential is between 0 volts and the potential of the first crossover. Here the secondary emission ratio is less than one and the surface charges negatively. This may be achieved by either pulsing the cathode negatively or by pulsing the storage mesh positively, capacitively raising the storage surface potential. The rate of erasure depends upon the S. E. ratio for each incremental area concerned. This, of course, is a function of the difference in potential between the area concerned and the viewing beam cathode potential. It should be observed that the erasure rate changes as the surface charges, going through a maximum where the S. E. ratio is a minimum and decreasing asymptotically thereafter as the surface approaches cathode potential. Single pulse overall erasure can be achieved in approximately 50 milliseconds providing the pulse is shaped to compensate for decreasing erasure rate which would otherwise obtain for a rectangular pulse (See Appendix).

Continuous partial erasure is achieved by applying a train of pulses at low duty cycle with a repetition rate greater than the critical flicker frequency. Under these conditions the observer will notice no perceptible change in brightness. When selecting the amplitudes and shapes of the constituent pulses of the pulse train

several factors must be considered. In a picture that consists of bright and less bright areas which signal should suffer more erasure, the weak signal or the strong signal? Should the percentage erasure or the amount of erasure be the same for all areas? The answer to these questions rests in whether the information desired is in the bright areas such as air targets in land clutter, in darker areas such as targets at sea against the noise, or in all areas as in a television picture. With PPI or television scanning systems the image repetition rate is the same for all parts of the picture. Therefore the characteristics of the erase pulse train can be adjusted for a persistence time which must and will be constant for all parts of the picture. However, the image repetition rate is not the same for all parts of a B scan. The required persistence time will vary with position in the picture. Since this mode of erasure provides, under any one set of conditions but one persistence time a compromise must be reached. In television it is desireable that the persistence be short enough to prevent smearing of the picture. The frame period is 1/30th of a second or 33 milli-seconds. If viewing, writing and erasing must all proceed simultaniously then it is apparent that time sharing of the viewing and erase functions must be employed. Neither choice of erasure, pulsing cathode or pulsing storage grid affects the writing operation. The change in the acceleration potential of writing electrons and the collection gradient is insignificant. The velocity of the erasure electrons will be the same in either case. A difference in the rate of erasure will then depend on some change in the nature of the mesh aperture lens characteristics. This is not

expected to change for insertion of the erasure signal at the viewing cathode but will undoubtedly change for injection of the erasure signal at the storage mesh. The effect of this change in the lens should be ascertained before selecting the electrode upon which to impress the erasure signal.

Selective erasure must be accomplished with a well focussed beam. This requirement initially suggests acceleration potentials in excess of the first crossover potential of the S. E. curve. The most appealing possibility at the outset is writing and erasing simultaneously with one beam above the second crossover employing cathode modulation and equilibrium writing. This is not practical for two reasons. First, the S. E. ratio is only slightly less than one above the second crossover and requires large changes in acceleration potential for small changes in storage surface potential. As a result both the writing and erasing rates would be prohibitively slow. Moreover, the storage surfaces display marked non-uniformity in the value of the second crossover potential over their surfaces. And finally the curve of S. E. ratio as a function of accelerating potential is decidedly non linear in the vicinity of the second crossover.

The possibility of erasing between crossover potentials where the S. E. ratio is greater than one suggests itself to provide high erasure speeds. A strong negative gradient at the storage surface contributed by the collector is a primary requirement in order to repel the secondaries back onto the storage surface to effect negative charging and to prevent redistribution of secondaries onto adjacent positive regions. Redistribution would reduce the rate of erasure and

broaden the erased line. In the written state a positive gradient exists to the storage mesh from the storage surface. This gradient remains regardless of the changes of potential on the various electrodes. The holes in the mesh provide a means by which secondaries may be collected by the more positive storage mesh. Inasmuch as operating gradients through the dielectric to the mesh are 100 to 400 KV per inch, establishing an over-riding repelling gradient with the collector would involve electrostatic forces that would soon rupture the collector mesh.

Selective erasure, if feasible at all, appears to be restricted to erasure below the first crossover potential. Normal incidence of the erasure electrons is necessary for erasure with low velocity electrons to insure that the normal component of velocity is fairly uniform over the entire surface of the dielectric. Small differences in velocity below the first crossover result in large differences in S. E. ratio which yield large differences in erasure rates. This requirement is no less rigid for overall erasure by the viewing gun. However, collimation is also a requisite for the primary function of the viewing beam.

If selective erasure and viewing are to proceed simultaneously the collimation of the erase beam must be achieved by the collimation lens designed for the viewing beam. The erase gun should, therefore, be placed at the focal point of the lens which is already occupied by the viewing gun. Since both guns cannot occupy the focal point some method might be used to make it appear that electrons originate on the axis near the focal point by magnetically bending the beam

from an electron gun offset from the axis. Attempted by RCA, this method was found to be impractical.

When the erase gun is not placed at the focal point of the lens but off-set parallel to the axis, proper collimation does not obtain. The angle of incidence of the collimated erase beam is a function of the deflection of the erase beam in the plane through the axis of the gun and the axis of the tube. The axial velocity of the electrons incident on the dielectric is a function of the angle of incidence. Because the angle of incidence varies with deflection, shading is observed in erasure. The application of a variation in the potential of the erase gun as a function of the deflection in the plane described has been attempted by RCA and has proved effective in reducing the shading.

The use of low erasure velocities makes it extremely difficult to produce a beam with sufficient erasing current in a small spot. The spreading of the beam is caused by space charge effect in the beam. A specialized erase gun capable of producing a high current density in a small spot is required.

Erasure rates of approximately 30 inches per second for a line approximately one tenth inch wide have been achieved. This speed may be compared with a writing speed of the order of 1 to 10 kilo-inches per second for a line .04 inches wide.

It is obvious that if complete erasure were to be demanded the erasing beam could not keep up with the writing beam. Consider a staircase raster where the written lines are tangent to each other. If the erase beam precedes the write beam by two lines and scans at

the same rate, the erase beam would, by overlapping written lines, partially erase two and one half lines for every one written by the writing beam. The time spent by the erase beam on any one written line would still be but .075 of that required for complete erasure from full high-light brightness. If, however, as is customarily the case, the spacing of the written lines is approximately the width of a written line, the erase beam would partially erase but one line for every written line. The time spent by the erase beam on any one line per scan would now be but .03 of the time required for full erasure from full highlight brightness.

The need for complete erasure is the next factor that should be considered. A certain amount of redundancy occurs at a given incremental area on the viewing screen from scan to scan for both television pictures and radar plots. Failure to erase completely results in some scan-to-scan integration. This becomes objectionable in a television picture when smearing becomes apparent to the viewer. However, in a radar picture a certain amount of scan-to-scan integration is quite often desireable.

This integration may put a tail on a moving target giving some indication of the track and speed of the target when the same size echo is received for each pulse transmitted. If the target goes into a fade the indicator indicates the last known relative position of the target which would be lost under fade conditions if complete erasure were achieved on each scan. Under fade conditions the observer would note no apparent change in relative position and a continuing decrease in echo strength and relative target speed caused by subsequent

partial erasures of the signal.

The previous discussion was for the case where the writing beam was writing almost continuously. In cases where the writing beam has a duty cycle the writing dead time may be profitably employed by the erase beam. Consider the case of a radar whose repetition rate is set for a range of 200 miles. If the range interval displayed by the radar indicator were 20 miles, as it often is when a surface search radar is used for navigation or off center examination of a long range target, the writing gun would be writing only during one-tenth of the period of the repetition frequency. Now were the erase beam advanced two or more scan lines ahead of the writing beam and the sweep period set equal to the repetition period, the time spent by the erase beam on any one line would be .75 of the time required for full erasure from full highlight brightness.

In this type of erasure the erasing signal has about the same absolute value as the cut-off potential of the storage surface. The initial rate of erasure for any elemental area of the storage surface will be roughly proportional to the difference between the potential of the particular area and cut-off. The rate decreases as erasure progresses. Consequently, it is reasonable to assume that erasure, even if it is not complete, proceeds to a point where all of the elemental areas have been erased to approximately the same background level, a level that may be very close to that for complete erasure.

8. Persistence

Persistence depends upon the following factors:

1. Landing, if any, of viewing electrons on the surface of the dielectric.
2. Leakage of electrical charge due to finite resistivity of the dielectric.
3. Landing of positive ions produced in the residual gas by the writing and viewing beams.

Electron landing occurs in this design only when some part of the dielectric surface attempts to go slightly positive. These electrons then charge the portion of the surface concerned back down to ground, the potential of the viewing cathode. Because viewing electrons are repelled from negative areas of the surface they cannot cause deterioration of the stored information.

The retention time τ of the stored charge pattern with all potentials removed from the tube is defined as the time required for the charge to decay to 1/e of its initial value.

$$\tau = 8.84 \times 10^{14} \; k\rho \text{ seconds}$$

where k is the dielectric constant and ρ the resistivity. Examples of retention time are those for the fluorides of barium and calcium which are 0.1 seconds and 50 hours respectively.

The decay of the stored picture caused by continuous viewing by the viewing beam is a function of viewing beam current, viewing duty cycle, gas pressure, capacity of the dielectric surface, and the choice of control characteristic. The rate of decay increases with beam current, duty cycle, and gas pressure and decreases with storage surface capacity and range of control characteristic.

A large beam current and a high duty cycle is required to achieve high levels of luminance. The storage surface must be reasonably thick to provide high writing speeds. The control characteristic (brightness as a function of storage surface potential) is a fairly linear function. Its useful range should be reasonably large in order to minimize the effects of non-uniformities. However, the range of storage surface potentials should not be so large that the writing gun is precluded from writing to full brightness at normal scanning rates.

Normal tube processing provides a residual gas pressure of 10^{-6} to 10^{-7} mm of Hg. Neither batalum nor zirconium getters seem to be effective at pressures less than 10^{-7} mm of Hg. By employing an ion gage integral with the storage tube RCA has been able to reduce the gas pressure from 10^{-7} mm to 10^{-8} mm of Hg. Once evacuated, Pyrex glass envelopes will leak helium. Because Kovar sealing FN glass is noticeably less susceptible to this type of leakage RCA has used this glass for the envelope.

Ions formed by the electron beams in the residual gas that are free to migrate to the storage surface will fade up the half-tone picture. The greater part of these ions may be repelled by making the collector mesh five to ten volts more positive than the wall electrode. Then only those ions formed in the collector to storage surface space will cause decay of the picture. Less than 10% of all ions formed in the tube cause the fading of the picture, a process that is, in general, linear with viewing time.

The useful viewing duration T_v is defined as the time required

for the background brightness to increase to ten per cent of the highlight brightness. For a half-tone picture this is approximately equal to the time required to raise the potential of the most negative area of the storage surface ten per cent of the useful storage surface potential range. For most radar applications ten to 20 seconds is adequate. One tenth of a second is adequate for television applications. Let:

C_s - capacitance of A, most negative region of storage surface

V_1 - initial potential of region A

V_2 - final potential of region A

I_{ion} - positive ion current landing in the region A, assumed to be constant

I_v - viewing beam current producing I_{ion}

Then:

$$V_2 - V_1 = \frac{1}{C_s} \int_{t_1}^{t_2} I_{ion}\, dt = (1/C_s)\, I_{ion}\, (t_2 - t_1)$$

and if $V_2 - V_1 =$ ten percent of the useful range of storage potential

$$t_2 - t_1 = T_v \qquad \text{and}$$

$$T_v = (V_2 - V_1)\, C_s\, (1/I_{ion})$$

I_{ion} may be estimated as a function of the tube potentials, tube pressure p, and the viewing beam current I_v.

The number of ions formed per electron of viewing beam current per cm of travel is given by:

$$N = \frac{6 \times 10^4\, p}{V} \qquad (21.16) \qquad [17]$$

where p is in mm and V, in volts, is the potential through which the electrons have been accelerated. If, for a typical case we take V as 150 volts and p as 10^{-7} mm of Hg then N = 4 x 10^{-5} ions/electron/cm travel. If the collector is spaced 1/4 inch (0.636cm) from the storage surface then N = 2.54 x 10^{-5} ions/electron. If we take the viewing beam current as 0.4 MA then for monovalent helium I_{ion} = 1.014 x 10^{-8} amperes. Finally, if C_s is of the order of 2 x 10^{-7} farads and the useful control range is 10 volts then

$$T_v = \frac{(1)\ 2 \times 10^{-7}}{1.014 \times 10^{-8}} = 20 \text{ seconds}$$

The capacity C_s, which in this case has been taken as the total capacity of the dielectric to the mesh, must be large and the ion current must be small if T_v is to be large.

$$C_s = \frac{k\,A}{11.1\,d} \times 10^{-12} \text{ farads}$$

The writing speed requirement that d, the thickness of the dielectric, be large is limited by physical considerations. A, then, must be large, but for a given pitch mesh this results in a decrease in transmission and a loss of high-light brightness. Furthermore as the transmission for a given size tube is reduced the control range gets smaller resulting in a smaller T_v. It is conceivable that the control range could be increased more than the capacity is decreased by increasing the pitch or reducing the cross section of the wires in

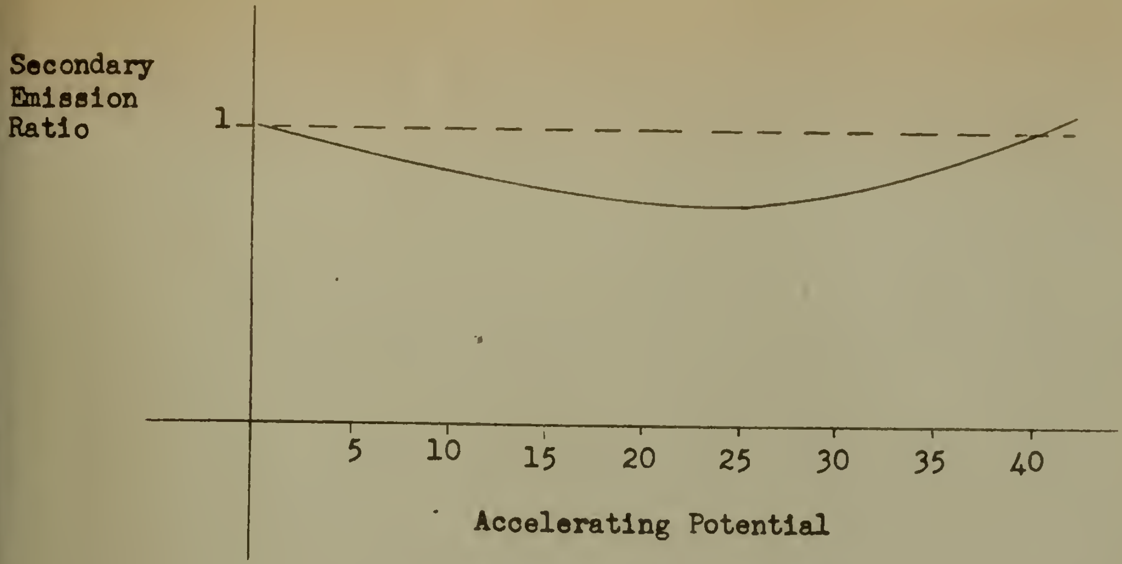
the mesh. However, the minimum pitch of the mesh is controlled by resolution requirements and the strength requirements limit the allowable reduction of the mesh wire cross-section. Consequently, a compromise must be made controlled by the demands made on the tube.

9. Holding

Holding is a term which describes a technique used to compensate for the fading up of a picture caused by positive ion landing. Holding would not be necessary of course, if the ions formed in the tube could be prevented from striking the storage surface. The use of an ion repeller between the viewing cathode and the storage surface will suppress most of the ions formed in the tube but as may be seen from the section on persistence some ions are generated in the space between the collector and the storage surface.

If we might assume that ion landing is uniform, uniform removal of charge from each incremental area of the storage surface would remedy the ion landing. This might be accomplished by erasing below the first crossover potential of the secondary emission ratio curve, pulsing the storage mesh at a frequency above the critical flicker frequency with a positive going low duty cycle pulse.

To obtain an idea of the type of pulses required it would be adviseable to consider the shape of a typical secondary emission ratio curve below the first crossover. For instance talc, as shown in Figure 7, might exhibit a minimum emission ratio of seven tenths at 25 volts and a maximum of one at zero volts and 40 volts.



Expanded Secondary Emission Curve

Figure 7

Assume that the control range of the storage surface is ten volts. Then a positive pulse of 25 volts would provide a maximum erasure rate for fully written areas and a positive pulse of 35 volts would provide a maximum erasure rate for unwritten areas. Pulsing the storage mesh alternately with 25 volt and 35 volt pulses would make the rate of charge removal nearly uniform over the storage surface. Because the negative slope is not equal to the positive slope some non-equality of the pulse durations may be needed. However, ion landing is not uniform being more pronounced in the center of the storage surface. Consequently, the method falls short of complete compensation. However retention of the picture under viewing conditions using the holding principle has been for as long as three minutes with some loss of half-tones in the process.

Intermittent Haeff holding may be used where the loss of half-tones is not of serious consequence. This technique uses between cross-over writing (secondary emission greater than one) for bright areas and below first cross-over erasure for less bright areas. Let us say that for the storage surface described above areas with potentials less than minus five volts are to be considered unwritten - those greater than minus five volts, written. A train of pulses of 45 volt amplitude would retain a black and white picture under viewing conditions for a period of 15 to 20 minutes before ions had written up the center of the picture. This technique is not worthy of consideration here because it destroys what the tube is specifically designed to produce - half-tones.

As may be expected from the ratio of ion current to viewing current in a typical tube ($1 \times 10^{-8} / 4 \times 10^{-4}$) duty cycles on the order of 6×10^{-5} seem to suffice for holding purposes. Holding, therefore, has negligible effect upon writing or erasing, either selective or overall.

10. Resolution and Redistribution

Resolution depends first upon the written resolution of the charge pattern on the storage surface, and second upon the focussing effect of the individual lenses of the storage mesh assembly.

The written resolution depends primarily upon the diameter of the writing beam which is about ten mils. If, during writing, all the secondaries emitted are collected by an electrode no redistribution of secondaries upon adjacent less negative regions of the storage surface

occurs. The change of charge distribution occurs only in the area immediately under the beam. To overcome large collection gradients of nearby written areas a strong collector field is required. This is difficult to achieve with the collector mesh. First of all, it is not truly planar even though it has been thermally stretched upon its supporting hoop. Second, it is fragile and should not be subjected to large changes in electrostatic forces. The gradient, however, must be large enough to overcome the suppression of secondaries by the coplanar grid effect of more negative adjacent areas which will be discussed in another section. Another source of collecting field is provided by the potential of the storage mesh which must be positive to give a control characteristic in the negative region. This gradient is of the order of 10^5 volts per centimeter whereas that for the collector is of the order of 10^3 volts per centimeter. Secondaries that do not emerge normally from the surface will probably travel laterally no further than the nearest hole where they will be captured by the field of the storage mesh.

The lens action of the storage mesh contributes to the resolution actually seen on the viewing screen. The spacing of the individual holes in the mesh must be at least as small as the resolution required. The dots formed by the elementary beams on the phosphor should not overlap for any brightness in the useful range. Circular holes when correctly made in photo-etched mesh form circular beams which image as dots on the viewing screen. However, the number of holes per linear inch that can be produced by this technique is less than 200.

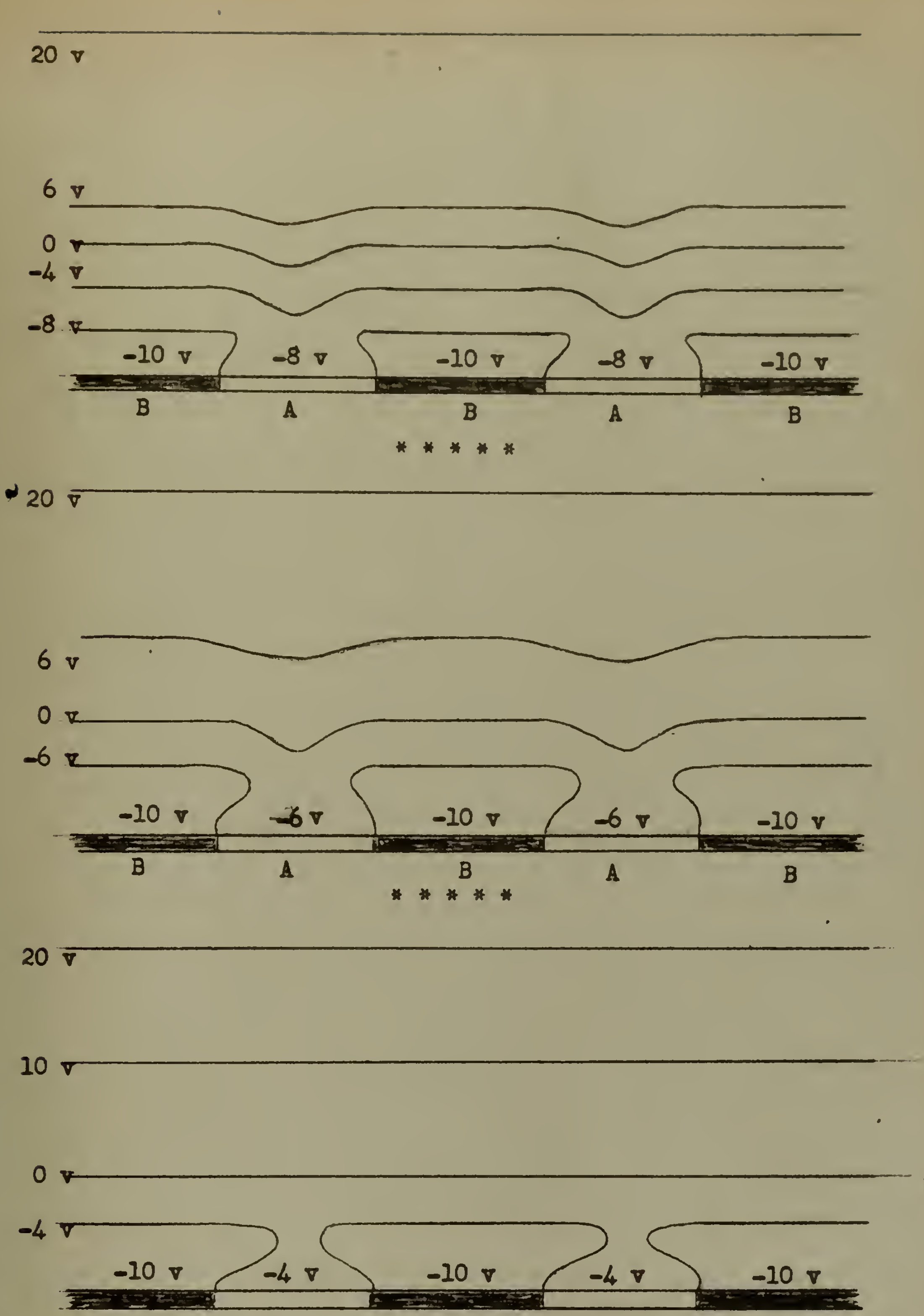
When even greater resolution is desired electro-formed mesh may

be used which may have as many as 700 holes per linear inch. The holes in this type of mesh are square and the beams formed by them produce astigmatic crosses on the viewing screen. It has been observed that overlapping of the dots occurs for conditions yielding less than full brightness. Moving the viewing plate closer to the storage surface would reduce the overlap, but would enhance the possibility of field emission caused by irregularities on either the storage assembly surface or the viewing screen. The deleterious effect of the overlapping of the elementary beams can be minimized by increasing the number of holes per linear inch which will cause some loss in transparency and maximum high light brightness.

11. Co-planar Grid Effect

Coplanar grid action is simply a grid control action imposed on secondary electrons emitted from one area of the storage surface by the field formed by adjacent areas at somewhat different potential. Figure 8 shows the co-planar grid effect becoming more prominent as area A becomes increasingly positive with respect to area B. Of course it also represents the case where area B becomes increasingly negative with respect to area A. Both concepts are used in analyzing either writing or erasing.

Writing is accomplished using a secondary emission ratio greater than one. Secondaries that are emitted from the area under the beam must be collected to cause the potential of the surface to rise positively. If, before writing, the storage surface is at some uniform negative potential, the secondaries emitted will be collected initially by the collector. As the area under the beam continues to charge



Potential Field of Coplanar Grid

Figure 8

positively the coplanar grid action begins to restrict the flow of electrons to the collector causing some low velocity electrons to fall back onto the surface under the beam. The charging progresses at a reduced rate until the coplanar grid effect chokes off the secondaries to the extent that the number collected equals the number impinging the surface. The area is then in a state of equilibrium and the surface ceases to charge positively.

Usually, however, the spot being written upon lies adjacent to written areas already charged to a more positive potential. The resultant action is somewhat different than that described above. The positive area surrounding the beam may collect a portion of the secondaries initially emitted if the gradient is sufficiently great. The landing of these secondaries on the storage surface is known as redistribution. The disturbance of the charge pattern by redistribution is known as interline modulation. As the area being bombarded rises to the potential of its immediate surroundings more and more of the secondaries will be collected by the collector. The charging process then continues in the manner described in the preceding paragraph until equilibrium is established. Of course, if the written potential exceeds ground potential the viewing beam will reduce the potential to that of the viewing cathode upon the removal of the writing beam from the area so charged.

A somewhat similar action occurs during erasure. Consider only erasure below the first crossover potential where the secondary emission ratio is less than one.

Overall erasure is accelerated by coplanar grid effect. The

less positive regions force some of the secondaries emitted from neighboring more positive areas back on to the areas from which they were emitted. Furthermore, certain of the secondaries emitted from the less positive regions are accelerated to the more positive area. Both these actions serve to bring the entire written surface to a uniform potential, permitting the use of rectangular erasure pulses.

Selective erasure is improved for areas more positive than the adjacent areas but redistribution occurs when the area being erased becomes more negative than its surroundings.

The writing and selective erasure functions, therefore require that the co-planar grid effect be minimized. The remedy is to provide a stronger gradient to the collector mesh. The value of gradient required will be a function of the maximum difference of potential expected between written and unwritten areas and the dimensions of the areas of unequal potential.

12. Background Noise and Non-Uniformities

If the half-tones in a half-tone storage tube are to have any significance the brightness of the background must be uniform. If a uniform background cannot be achieved, the variation in the amplitude of the background must be minimized. If the useful brightness range of the tube is to be 20 d.b. from the background to full brightness then the background should not exceed one per cent of the total brightness. If the storage surface potential vs. brightness characteristic is linear the effective delta cut-off should not exceed one per cent of the control range, one-tenth volt for a range of ten volts. Because the control characteristics are slightly remote cut-off and because

one per cent of the control range is difficult to achieve for delta cut-off a figure of ten per cent is considered good.

The major factors contributing to non-uniformity of the background are variations in the storage mesh lens characteristics near cut-off, deflection effects caused by the residual magnetism in magnetic material used in the tube, non-uniform secondary emission characteristics, and moire. Other equally significant factors are poor collimation and non-uniform storage surface thickness which have been discussed elsewhere. Variations in the lens characteristics are caused by non-uniform storage mesh wire and hole diameters. It has been estimated that variations in these dimensions should be maintained at less than one per cent [18] . The dimensions of electro-form mesh are easier to control than those of etched mesh due to the techniques employed in their manufacture, which is one reason for the more prevalent use of the former type. Resolution specifications generally permit somewhat larger hole diameters and hole spacing in larger diameter tubes. The percentage variation of these two dimensions is, therefore, easier to control.

Magnetic poles in the mounting hoops cause undesired deflection of the viewing electrons. This contribution to non-uniformity is minimized by reducing the mass of magnetic materials used in the tube and by a complete demagnetization of the tube following processing.

Non-uniform secondary emission characteristics of the dielectric surface causes variations in the writing and erasing speeds. The non-uniformity of the secondary emission characteristic over the surface of the mesh may be determined with a tube having good collimation by

operating the tube in the bistable mode.

This might be achieved in the following manner. The collector is grounded, the viewing cathode and the storage mesh are connected to the negative terminal of voltage source V. V is increased to some acceleration potential well in excess of the expected first crossover potential. The entire dielectric charges to ground potential of the collector, and viewing electrons pass through the storage mesh illuminating the entire viewing screen. The potential V is then decreased until the first crossover acceleration potential has been reached for some elemental area. This area will discharge to cathode potential, preventing the passage of electrons through it to the viewing screen, resulting in a dark patch. As the potential V is decreased further, more areas discharge to the cathode potential, spreading the dark spot until it encompasses the entire viewing screen. A map can be made from these patterns delineating the areas of the surface whose first crossover potentials lie between any two voltages. A similar method may be used to obtain a secondary emission pattern at the second crossover.

It has been observed that bombarding the storage surface during processing of the tube lowers the first crossover potential by a uniform amount for all areas comprising the storage surface. Thus the percentage non-uniformity is increased.

The mal-effects of secondary emission non-uniformities are minimized by careful selection of the dielectric material after tests described above have been performed and by the omission of the bombardment of the storage assembly during processing of the tube.

Moire is an interference pattern similar to that observed when looking through two parallel screen doors. The effect can be minimized by proper orientation of the screens one to the other. The best orientation is estimated by visual observation and finally selected after observation in the tube.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Transmission control bright display storage tubes using the techniques described for the RCA tube are capable of producing a long persistence, high brightness display which for black and white television is characterized by good fidelity in half tone reproduction. Before embarking upon a discussion of the feasibility of using these devices for radar indicators it would be appropriate to discuss some of the limitations of the tube and the direction in which expected design progress is to go.

It is significant that erasing speeds are not as fast as writing speeds. The tendency has been to further increase writing speed so that high speed transients may be recorded properly, compounding the erasing problem. Unfortunately the only feasible way to increase writing speed and erasing speed concurrently is the use of a thicker storage surface which has deleterious effects on the useful viewing duration. The only feasible way to compensate for decreased viewing duration without impairing writing speed or brightness is the use of lower pressures in the tube. Pressures of 10^{-7} and 10^{-8} mm of Hg are already lower than those obtained at present with conventional commercial practice. Use of these and lower pressures contributes heavily to the cost and difficulty of mass production.

Irregularities in collimation, storage surface thickness, secondary emission, and storage mesh dimensions together with the multiplicity of electrodes in the tube contribute a significant amount of internal

noise. A long control range is required to minimize the effects of this noise. The gradients required to give a long control range have been increased to their practical maximums. The only other means of extending the control range appears to be some means of reducing the proportionate dielectric area about each storage mesh hole. In large diameter tubes the resolution requirements are such that more transparency can be achieved in the storage mesh by reducing the number of holes per inch. In small tubes the only feasible solution is the developement of a technique to remove some dielectric from the vicinity of each hole. The remaining dielectric must be symmetrically distributed about the hole to insure uniform focussing, otherwise sufficient additional noise would be introduced to nullify the advantages of the extended control range.

Further developement in the design of the tube is, therefore, pointed toward commercial methods of hard pumping and techniques required to extend the range of the control characteristic.

The direct viewing storage tube offers the immediate advantage of increased brightness and extended persistence. These qualities commend its use as an indicator for the operator who may be occupied concurrently with other tasks. Navigators, pilots, and officers-of-the-deck will be gratified by the freedom this new device will permit them to prosecute their other tasks. The high brightness feature permits the operation of the tube without the customary hood required by other indicators in all daylight locations except under direct strong sunlight. The average brightness of the picture on the face of the tube should be that brightness to which the observer's eyes

are acclimated. This may be achieved by designing the tube for exceedingly high brightness and providing polaroid filters to permit adjustment to the ambient luminance level.

Because the tube must, for best performance, be operated at brightness levels equivalent to or greater than daylight indoor lightning, combat information center can be freed of its cloak of darkness with a resultant increase in efficiency and endurance on the part of its operating and maintenance personnel.

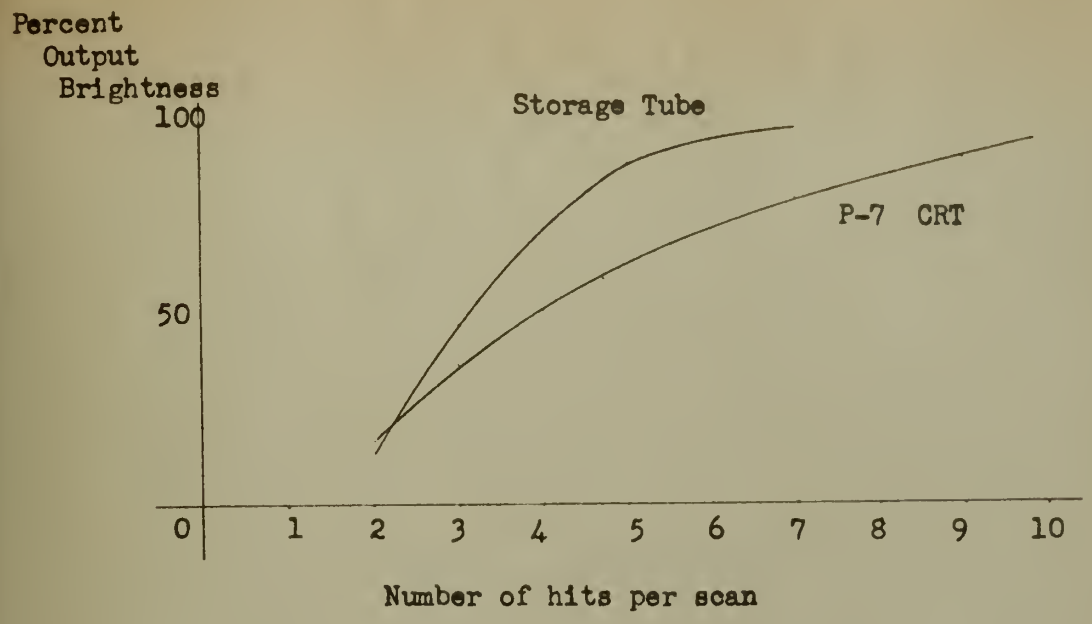
The eyes of night fighter pilots and night officers-of-the-deck are normally dark adapted. Operation of the tube at luminance levels greater than 10 foot lamberts is therefore undesireable if these operators are to retain their dark adaptation. It becomes immediately apparent that the ability of these operators to detect weak echoes will be negligible for two reasons. One, because of the press of other duties they will not have time to efficiently scan the indicator and two, their eyes are forced to operate at their poorest performance level. The inability to see targets at the optimum range is a distinct disadvantage for the pilot of a high speed fighter because the time available to consumate an attack is extremely limited. It is reasonable to expect that both the pilot and the officer-of-the-deck will be coached onto the target by other personnel who have made early detection. Initial action will be instituted on the basis of these reports. The target will soon thereafter become visible on the indicator of the pilot or OOD. The storage tube then becomes, for the night pilot and night officer-of-the-deck, a reference map from which to carry out the remainder of the action.

The choice of operating brightness is difficult to choose for these conditions because the dark adapted eye is most sensitive between 0.7 foot lamberts and 7 foot lamberts, where its response is logarithmic [1] . Exposure much in excess of two tenths of a second to these luminances will, however, cause a loss of dark adaptability, forcing the use of lower luminance levels with coincident decreased sensitivity and lack of logarithmic response.

Half-tones are important in a radar indicator to facilitate the recognition of one signal against a background of other signals. Two important instances of this occur; one, a target echo in a background of communication channel noise, and two, a target echo in a background of sea return or clutter. These two requirements of a radar indicator influence the manner in which the radio frequency and video signals are to be amplified and the choice of shape for the control characteristic.

The use of a linear-logarithmic intermediate frequency amplifier, a linear detector, and a linear control characteristic should provide a visual signal giving sufficient luminance variations to improve detection in noise or clutter. The amplitudes of the weak signals and the noise will be expanded at the expense of the strong signals and clutter.

The detection of weak signals in noise is enchanced by integration - both writing integration and scan-to-scan integration. Figure 9 shows a per scan comparison of the integration properties of the storage tube and the P-7 phosphor CRT. If partial erasure is employed scan-to-scan integration occurs. Random noise is more completely



Comparison of Signal Integration -
Storage Tube and Cathode Ray Tube

Figure 9

erased than the repetitive signal. However, one serious source of noise is not suppressed by this technique. The noise contributed by non-uniformities is repetitive yielding spots, the luminance of which will be approximately that expected of a weak target. Although a valid target may be distinguished by its relative speed, internal noise does reduce the efficacy of the tube because the operator is required to either familiarize himself with the pattern of this noise or to expend time evaluating false targets. The saving grace of a long control range is that it may be sufficiently long so that the amplitude of the radio frequency noise is substantially larger than the tube noise, minimizing the effects of the latter.

Integration also improves the probability of detection of signals in sea return. In this case the clutter is somewhat random and of

sufficient magnitude to minimize the effects of internal noise. If the target is to be observed it, too, must have a strong echo.

For naval fighter director work where the pips are well defined the tube has definite advantages. Present day jets in some angles of attack to the radar antenna offer poor reflective surfaces and fades quite often occur. The persistence of the tube will permit the controller to keep the last known position of the aircraft on the face of the tube. The pip length and intensity will be reduced by subsequent erasure. With training the operator will be able to recognize this phenomenon, not as a change of speed but as a fade because the relative distance to the target will not have changed and the pip will not have brightened on the passage of the sweep trace. An experienced controller might then dead reckon the aircraft's position ahead until he finds the next pip from the target.

The indicator might prove to be a useful adjunct to submarine attack radar where it could display one scan of the target area for a controlled period of time during which the antenna could be retracted.

If selective erasure is not required magnetic deflection of the writing gun may be achieved. Such a developemental tube is being built by Hughes Aircraft Company.

The tube apparently has sufficient applicability to warrant its use in its present form. It is this observer's opinion that this type of tube would prove superior to the conventional P-7 for all applications except perhaps early warning search. Even so, subjective tests should be made at an early date pitting the P-7 against the storage tube.

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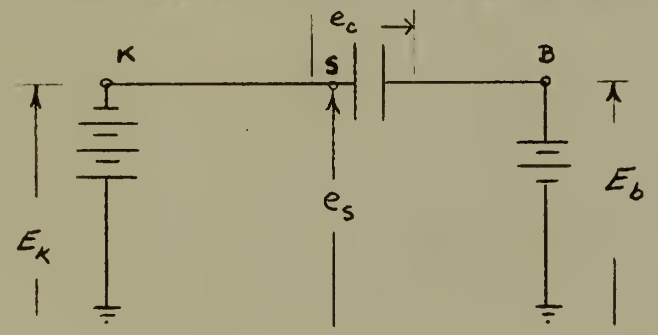
APPENDIX

Derivation of Erasing Speed

The primary current from the erasing cathode reaching the storage surface is $I_p \alpha_1 (1-\alpha_2)$ or $I_p \alpha \beta$ where $\alpha = \alpha_1$ and $\beta = (1-\alpha_2)$; α_1 and α_2 are respectively the tranamission of the collector and storage meshes. The net electron current flow, i, to the storage surface is $I_p \alpha\beta (1-\delta)$

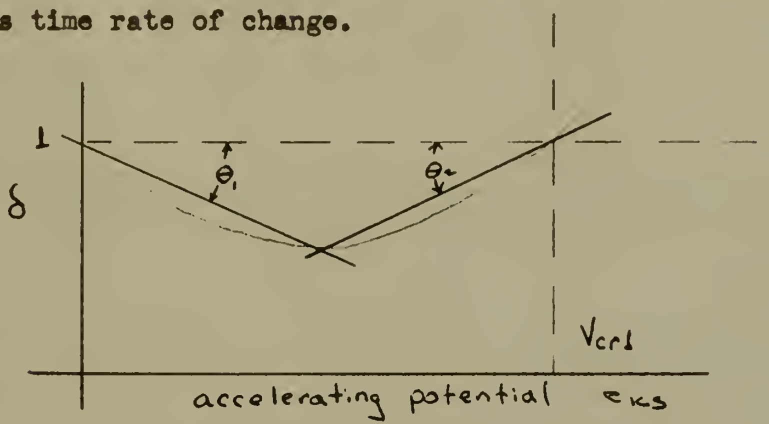
The storage assembly constitutes a capacitor, the dielectric surface being one plate and the storage mesh the other. A schematic representation of the erasing phenonomon is shown below.



Since $\frac{de_c}{dt} = \frac{i}{c}$ the storage surface potential, e_s, will change linearly with time if i and either E_k or E_b are maintained constant. However, $i = \alpha\beta\ I_p\ (1-\delta)$ and varies with e_s. If, however, E_b being held constant, the potential E_k is varied linearly with time to keep the potential e_{ks} constant δ and i remain constant and e_s will vary linearly with time.

That portion of the secondary emission curve below the first crossover can be represented conveniently by two straight lines as shown below. If e_{ks} is less than V_{cr1} for an initial value of i E_k must linearly increase in magnitude to maintain i constant. It should be recalled that for a half tone picture the value of e_s varies over the dielectric

surface. Fast rates of erasure for either strong or weak recorded signals may be provided for by the choice of erasure pulse amplitude and its time rate of change.



If E_k and E_b are maintained at constant amplitude during erasure the erasure rate is exponential as shown below.

For e_{ks} giving a value of δ on negative slope:

$$\delta = -\tan\theta_1 \; E_{ks} + 1$$

$$i = \alpha\beta I_p \tan\theta_1 \, e_{ks}$$

$$e_{ks} + e_c = E_B - E_K = E_{KB}$$

$$i = \alpha\beta I_p \tan\theta_1 \,(E_{KB} - e_c)$$

$$\frac{de_c}{dt} = \frac{i}{c}$$

$$\frac{de_c}{dt} = \frac{\alpha\beta}{c} I_p \tan\theta_1 \, E_{KB} - \frac{\alpha\beta}{c} I_p \tan\theta_1 \, e_c$$

$$e_c = E_{KB} - (E_{KB} - e_o)\,\epsilon^{-\frac{I_p \tan\theta_1 \alpha\beta}{c} t}$$

$$e_s = E_B - e_c$$

$$e_s = E_K + (E_B - E_K - e_o)\,\epsilon^{-\frac{I_p \tan\theta_1 \alpha\beta}{c} t}$$

where $e_o = e_c\,(0+)$

For e_{ks} giving a value of δ on positive slope:

$$\delta = \tan\theta_2 \left(E_{KS} - V_{CR_1} \right) + 1$$

$$i = -\alpha\beta\, I_p \tan\theta_2 \left(E_{KB} - e_c - V_{CR_1} \right)$$

$$\frac{de_c}{dt} = \frac{i}{c}$$

$$\frac{de_c}{dt} = \frac{\alpha\beta\, I_p \tan\theta_2}{c}\, e_c + \frac{\alpha\beta\, I_p \tan\theta_2 \left(V_{CR_1} - E_{KB} \right)}{c}$$

$$e_c = -\left(V_{CR_1} - E_{KB} \right) + \left[e_o + \left(V_{CR_1} - E_{KB} \right) \right] \epsilon^{\frac{\alpha\beta I_p \tan\theta_2}{c} t}$$

$$e_s = E_K + V_{CR_1} - \left[e_o + \left(V_{CR_1} - E_{KB} \right) \right] \epsilon^{\frac{\alpha\beta I_p \tan\theta_2}{c} t}$$

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